June 21, 2000

TO: Mr. Chris Abe
South Coast Air Quality Management District
21865 E. Copley Drive
Diamond Bar, CA 91765-4182

FROM: Vlad Ulmet
Department of Emissions Research

SUBJECT: Monthly Progress Report No. 2 for the period May 1 to June 1, 2000; Contract No. 00130, "Evaluation of Emissions Durability of Off-Road LPG Engines Equipped with Three-Way Catalysts," SwRI Project No. 08.03661.

I. PROGRESS FROM MAY 1 TO JUNE 1, 2000

A. Task 2 - Collect Emission Data and Determine Emission Control System Deterioration Factors

1. Steady-State Emissions Measurements

The main goal of this project is the assessment of emission control system durability by examining the performance deterioration of three-way catalyst systems installed on two forklift trucks over more than 4000 hours of real life usage. To determine the sources of deterioration, individual emission components were replaced with new components, and the engines were retested. Both the Mazda and the GM engines have completed steady-state testing in the following configurations:

- “As Found” (AF) — engine out - no catalyst, old (aged) catalyst (OC), new catalyst (NC)
- “Fueling adjustments" (F) (if necessary) — engine out - no catalyst, old (aged) catalyst (OC), new catalyst (NC)
- “New Oxygen Sensor” (NS) — engine out - no catalyst, old (aged) catalyst (OC), new catalyst (NC)

- “Maintenance” (M) — engine out - no catalyst, old (aged) catalyst (OC), new catalyst (NC)

- “Best Calibration” (BC) for NO_x — engine out - no catalyst, old (aged) catalyst (OC), new catalyst (NC)

Each of the above 15 configurations was tested in the seven shaded modes listed in Table 1, which were used as the basis for the ISO 8178-4 C2 cycle calculation. Mazda engine mode 22 was found to be considerably leaner than the other modes. Mixer "fueling adjustments" (F) were made for this mode, and the engine was then retested to show the effect of this adjustment. The periodic maintenance procedure, performed in accordance with the OEM service manuals, consisted of spark plug replacement, ignition timing adjustment, valve lash adjustment, and cleaning of the mixer. A "best calibration" (BC) for NO_x was developed and emissions map data covering all the points in Table 1 were obtained. Rated speeds were determined as follows:

1. Generation of lug curve. Measure maximum power vs. engine speed per 40 CFR 86.1332.

2. Normalization of lug curve. Normalize the lug curve by:
   - Identifying the point (power and speed) on the lug curve where maximum power occurs;
   - Normalizing the power values of the lug curve by dividing them by the maximum power and multiplying the resulting values by 100; and
   - Normalizing the engine speed values of the lug curve by dividing them by the speed at which maximum power occurs and multiplying the resulting values by 100.

3. Determination of rated speed. Calculate the rated speed from the following speed factor analysis.
   - For a given power/speed point, the speed factor is the normalized distance to the power/speed point from the zero-power, zero-speed point. The value of the speed factor is defined as:

$$\text{Speed factor} = \sqrt{(\text{power})^2 + (\text{speed})^2}$$

4. Determine the maximum value of speed factors for all the power/speed data points on the lug curve. Rated speed is defined as the speed where the maximum value for the speed factor occurs.

TABLE 1. STEADY-STATE TEST MODES [a]

Mode	Speed (% from idle to rated)	Torque (% at that speed)	Mode	Speed (% from idle to rated)	Torque (% at that speed)
1	**idle**	**—**	**19**	**60**	***50***
2	20	10	**20**	**60**	***75***
3	20	25	21	60	85
4	20	40	**22**	**60**	**100**
5	20	55	23	80	10
6	20	70	24	80	25
7	20	85	25	80	40
8	20	100	26	80	55
9	40	10	27	80	70
10	40	25	28	80	85
11	40	40	29	80	100
12	40	55	30	rated	10
13	40	70	**31**	**rated**	**25**
14	40	85	32	rated	40
15	40	100	33	rated	55
16	**60**	**10**	34	rated	70
17	**60**	**25**	35	rated	85
18	60	40	36	rated	100

[a] C2 modes are bold and shaded. Note that modes 19 and 20 depart from the pattern to fit the C2 cycle.

Since the rated speed definition described above differs from the ISO 8178-4 procedure, the Mazda engine was also tested referencing the true rated speed of the engine, at which maximum power occurs. This result is presented as Mode 37, and may be compared to the mode 36 result which uses the above described rated speed definition. Differences in rated speed and power for the Mazda and GM engines are shown in Table 2.

TABLE 2. RATED SPEED AND POWER

	Mazda Engine		GM Engine	
	rpm	hp	rpm	hp
Speed Factor Procedure	2,533	35.7	2,631	29.5
ISO Procedure	2,440	37	2,171	32

Forklift engines operate at idle with high auxiliary loads from the engine cooling fan and hydraulic pump. These loads were simulated in the test cell with the dynamometer. To maintain the target 600 rpm idle speed, a load of over 30 lb-ft was applied to the Mazda engine, and a load of 60 lb-ft was applied to the GM engine. For the no-load idle test mode, the speed governor had to be deactivated, and the idle speed readjusted. Also, at no-load idle, the catalysts are below their light-off temperatures, and therefore not reducing emissions. In order to cover both real life operation and the ISO procedure requirements, two idle modes were run on both engines in all tests. Mode 1 was idle with load, typically described as Curb Idle Transmission Torque (CITT). Mode 1A was no-load idle. Through the addition of these supplemental modes, a total of four different composite emissions results could be calculated for the Mazda engine, and two different composite results for the GM engine. These are summarized in Table 3. Differences in emissions were generally small, with a small NO_x response observed with the loaded idle mode.

TABLE 3. IMPACT OF MODE DEFINITION ON EMISSION RESULTS
BEST CALIBRATION, NEW CATALYST

Engine and Modes	C2 Emissions, g/hp-hr			BSFC, lb/hp-h
	HC	CO	NO_x	
Mazda Engine				
ISO Rated Speed, CITT>0	0.21	1.56	0.49	0.59
ISO Rated Speed, CITT=0	0.28	1.56	0.30	0.57
EPA Rated Speed, CITT>0	0.21	1.59	0.49	0.59
EPA Rated Speed, CITT=0	0.28	1.59	0.30	0.57
GM Engine				
EPA Rated Speed, CITT>0	0.10	0.30	0.44	0.68
EPA Rated Speed, CITT=0	0.11	0.28	0.14	0.65

Unless otherwise stated, results reported under this work assignment are based on speed factor rated speed and no-load idle. Detailed results using the different mode definitions can be found in Appendix C for the Mazda engine, and Appendix D for the GM engine.

Mazda Engine (Truck 16)

As identified on-site at Trout Apples, the oxygen sensor on this engine was malfunctioning, allowing operation at richer than normal air-fuel ratios. However, during engine start-up in the test cell, it was observed that the engine was running lean. A crack was found at the base of the throttle body which had become “unplugged” as a result of the steam cleaning of the engine prior to test cell installation. Accumulated dirt had apparently kept the crack sealed when tailpipe emission measurements were being taken on-site. A new throttle body was procured and installed during the maintenance procedure. For initial testing, an epoxy patch was applied over the crack. During the first set of “As Found” tests, it was observed that in Mode 22 (intermediate speed, full load), the engine was running very lean. For subsequent tests, this was corrected by opening the power valve from its initial position of approximately 2/3, to full rich.

Table 4 contains the description of the individual 9-mode tests performed on this engine, and the acronyms used in the legends of the graphical presentations of the results.

GM Engine (Truck 29)

One of the two identical substrates inside the catalytic converter muffler from Truck 29 was loose, and was reduced in volume by abrasion due to vibration. The catalyst parts were removed from the original converter and re-canned with a loss of only 18 percent in total catalyst volume. This canning problem was most likely caused by inadequate tolerance control in production.

Table 5 contains the description of the individual 8-mode tests performed on this engine, and the acronyms used in the legends of the graphical presentations of results.

Results from steady-state tests performed on both engines are presented in Figures 2 to 41. Figures 2 through 5 show C2 cycle results for both engines using both old and new catalysts. Figures 6 and 7 show catalytic muffler inlet temperatures for both engines. Figures 8 through 25 show detailed modal emissions results for both engines, both with and without the catalysts. Figures 26 through 29 summarize C2 CO and HC+NO_x emissions for all test configurations. Figures 30 through 41 present the full emissions map for both engines, with emissions plotted versus engine speed and load. Detailed results are in Appendix A for the Mazda engine, and Appendix B for the GM engine.

TABLE 4. MAZDA ENGINE TEST MATRIX CODES [a] (TRUCK 16)

	As Found (AF)		Fuel Adjustment (F)		Fuel Adjustment + Maintenance (F&M)
	Old Sensor (OS)	New Sensor (NS)	Old Sensor (OS)	New Sensor (NS)	New Sensor (NS)
No Cat (NC)	A	B	J	K	L
Old Cat (Old_C, (OC))	C	D	I	H	M
New Cat (New_C, (NC))	E	X	F	G	N
Old Cat					O (Cal. 1)
Old Cat					P (Cal. 2)
Old Cat					Q (Cal. 3)
Old Cat					R Cal. 4)
New Cat					S (Cal.3)
New Cat					T (Cal. 4)
New Cat					U [b] (Cal. 4)
No Cat					V (Cal. 4)
Old Cat					M1/M2/M3/M4 [c] (Cal. 4)

[a] Codes designate individual 9-mode tests
[b] Run in open loop
[c] Groups of modes to comprise complete emissions map

TABLE 5. GM ENGINE TEST MATRIX CODES [a] (TRUCK 29)

	As Found (AF)	Maintenance (M)
	Old Sensor (OS)	New Sensor (NS)
No Cat (NC)	GA	GF
Old Cat (Old_C, (OC))	GC	GD
New Cat (New_C, (NC))	GB	GE
Old Cat		GH (Best cal.)
New Cat		GG (Best cal.)
No Cat		GI (Best cal.)
Old Cat		GJ/GK/GL/GM/GN [b]
New Cat		XG/XGO/XGP/XGQ [b]

[a] Codes designate individual 8-mode tests
[b] Groups of modes to comprise complete emissions map

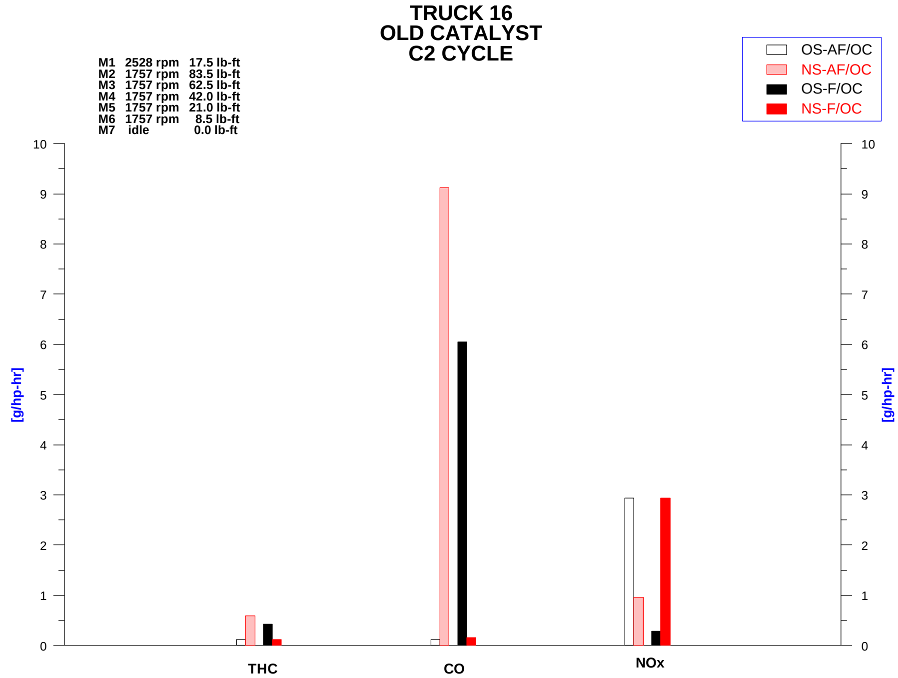

FIGURE 2. TRUCK 16, OLD CATALYST, C2 CYCLE RESULTS

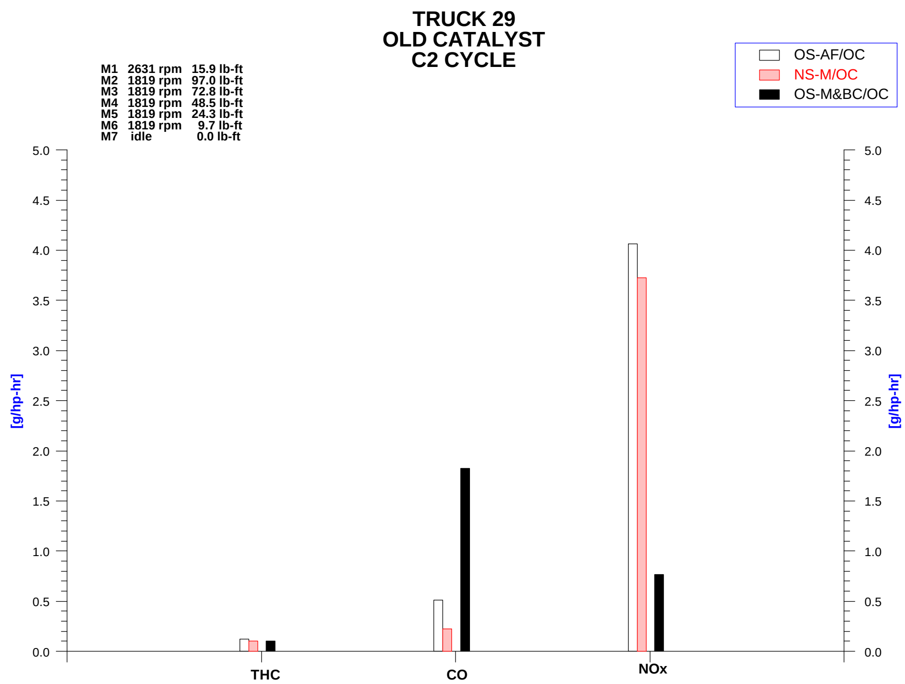

FIGURE 3. TRUCK 29, OLD CATALYST, C2 CYCLE RESULTS

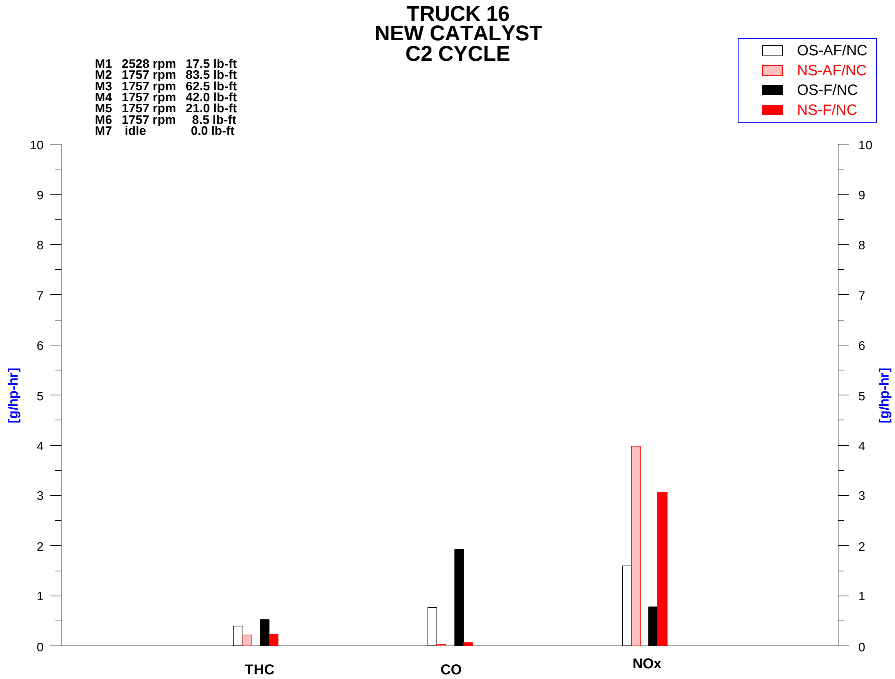

FIGURE 4. TRUCK 16, NEW CATALYST, C2 CYCLE RESULTS

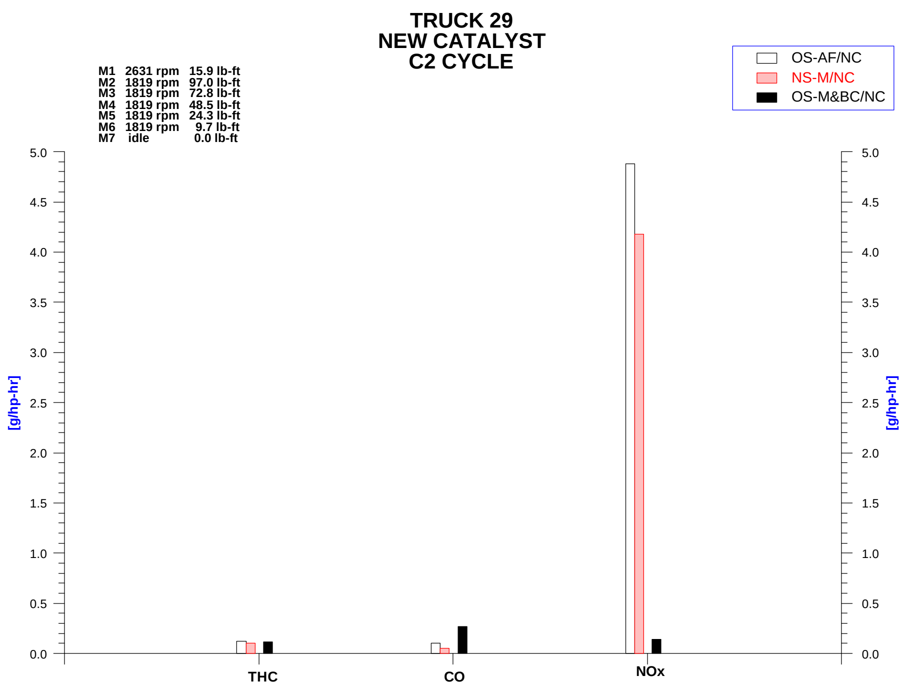

FIGURE 5. TRUCK 29, NEW CATALYST, C2 CYCLE RESULTS

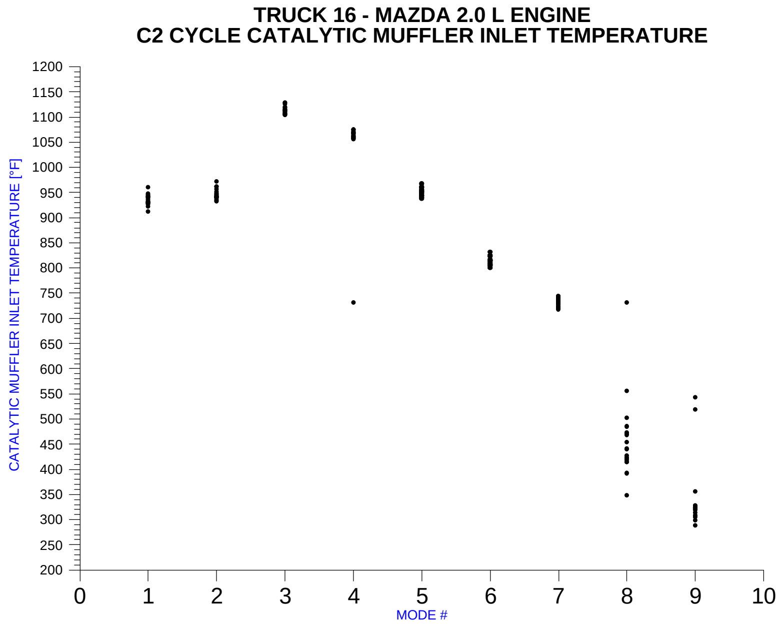

FIGURE 6. TRUCK 16, MAZDA 2.0 L ENGINE, C2 CYCLE CATALYTIC MUFFLER INLET TEMPERATURE RESULTS

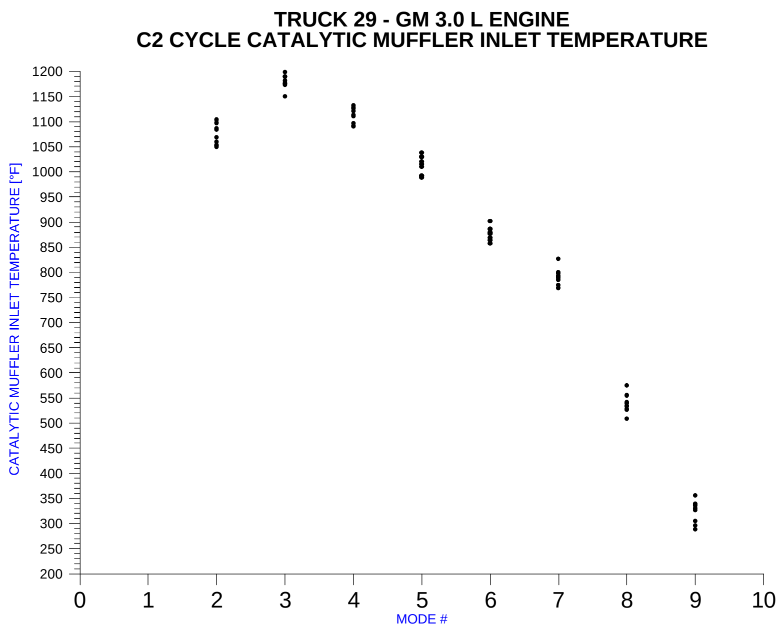

FIGURE 7. TRUCK 29, GM 3.0L ENGINE C2 CYCLE CATALYTIC MUFFLER INLET TEMPERATURE RESULTS

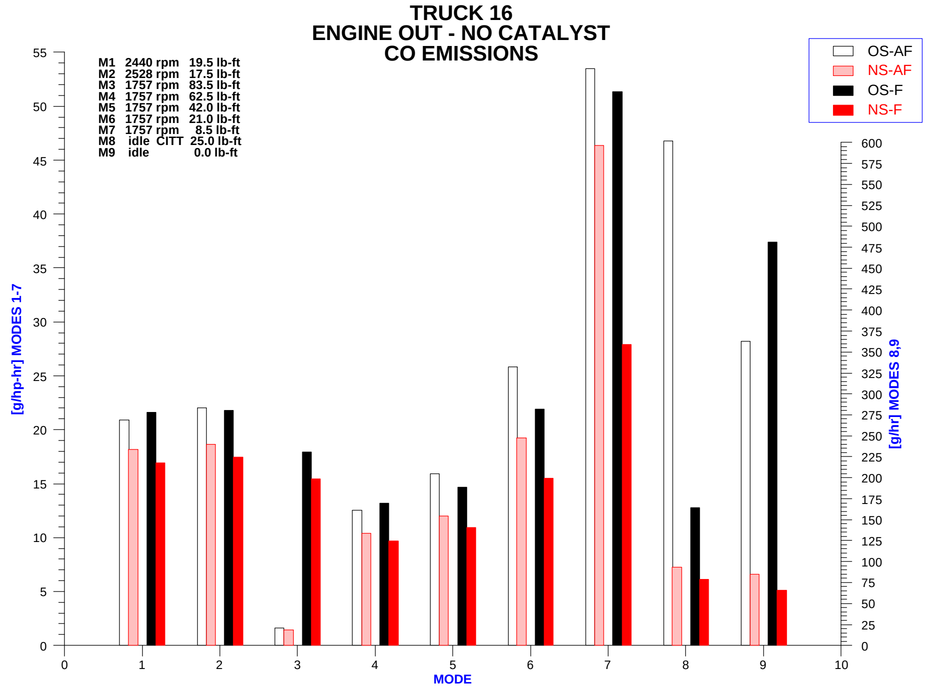

FIGURE 8. TRUCK 16, ENGINE-OUT - NO CATALYST CO EMISSIONS RESULTS

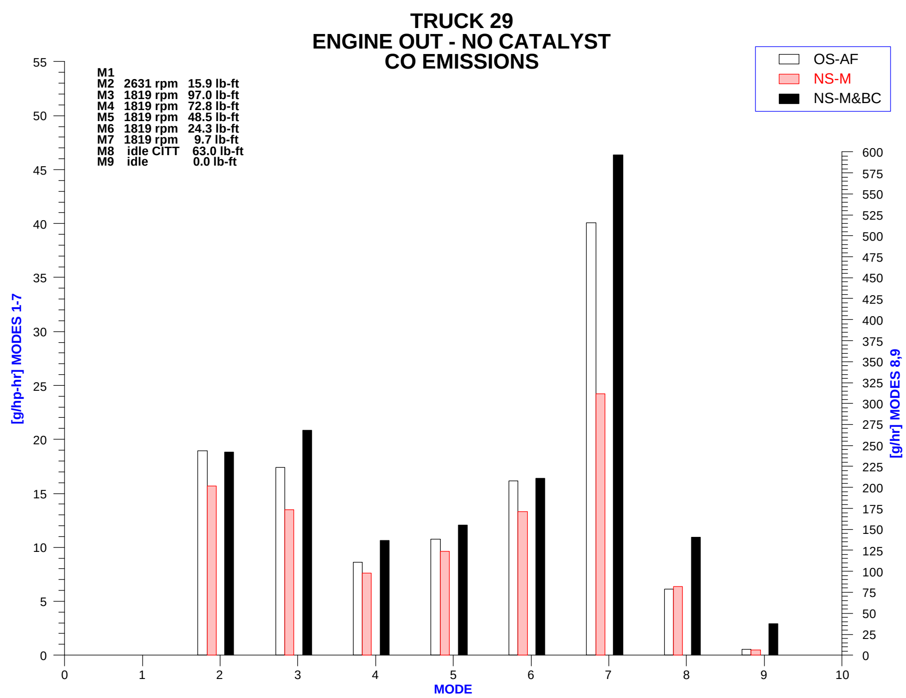

FIGURE 9. TRUCK 29, ENGINE-OUT - NO CATALYST CO EMISSIONS RESULTS

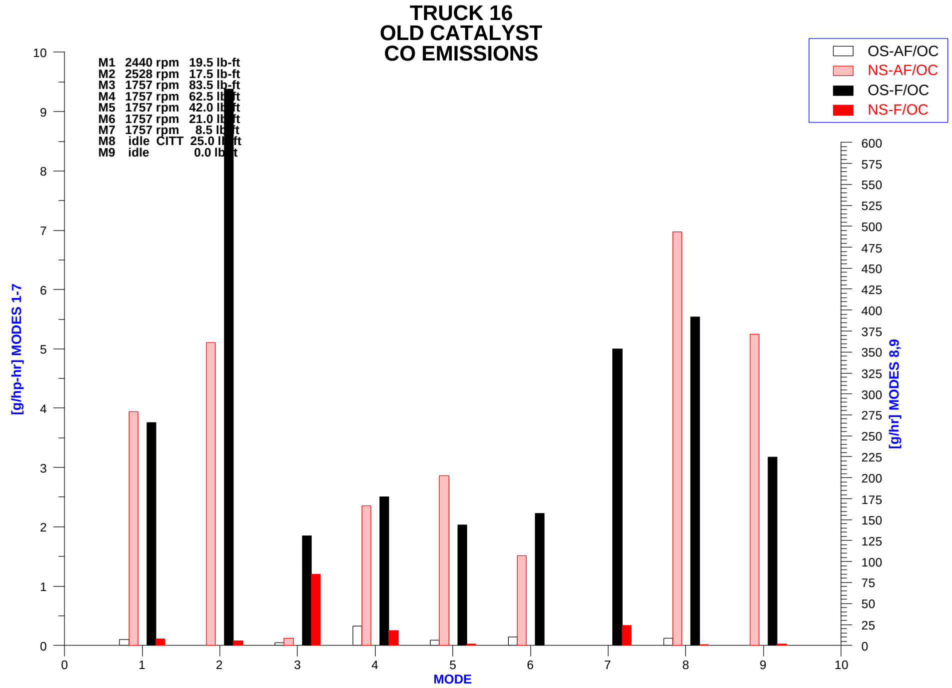

FIGURE 10. TRUCK 16, OLD CATALYST, CO EMISSIONS RESULTS

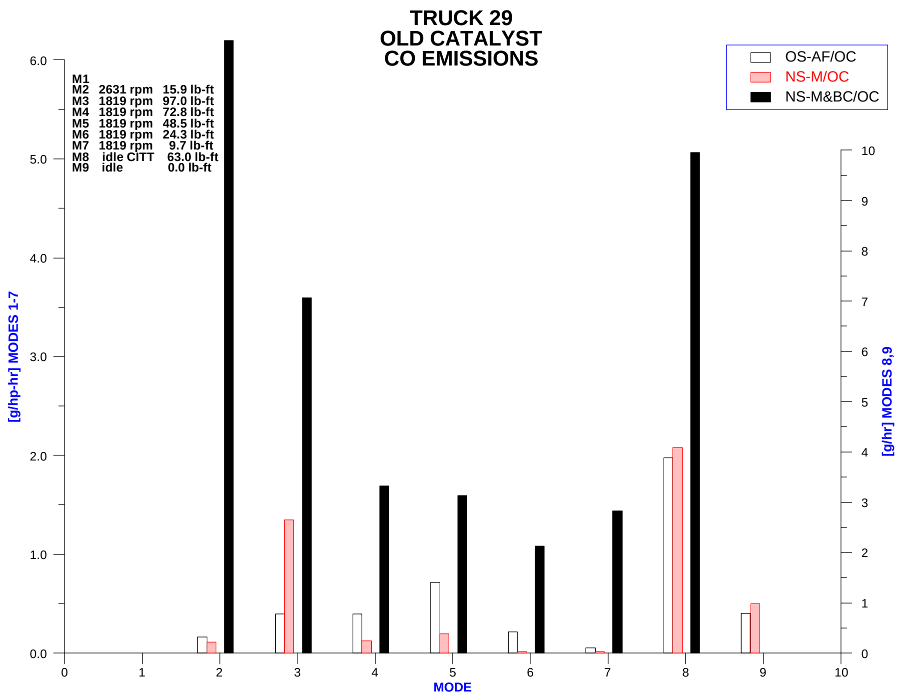

FIGURE 11. TRUCK 29, OLD CATALYST, CO EMISSIONS RESULTS

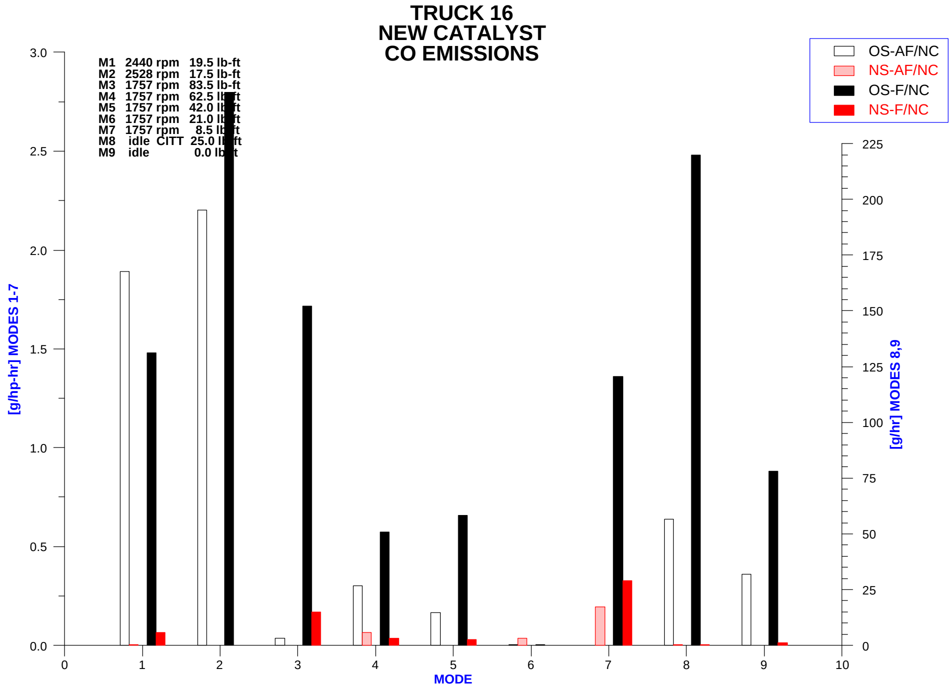

FIGURE 12. TRUCK 16, NEW CATALYST, CO EMISSIONS RESULTS

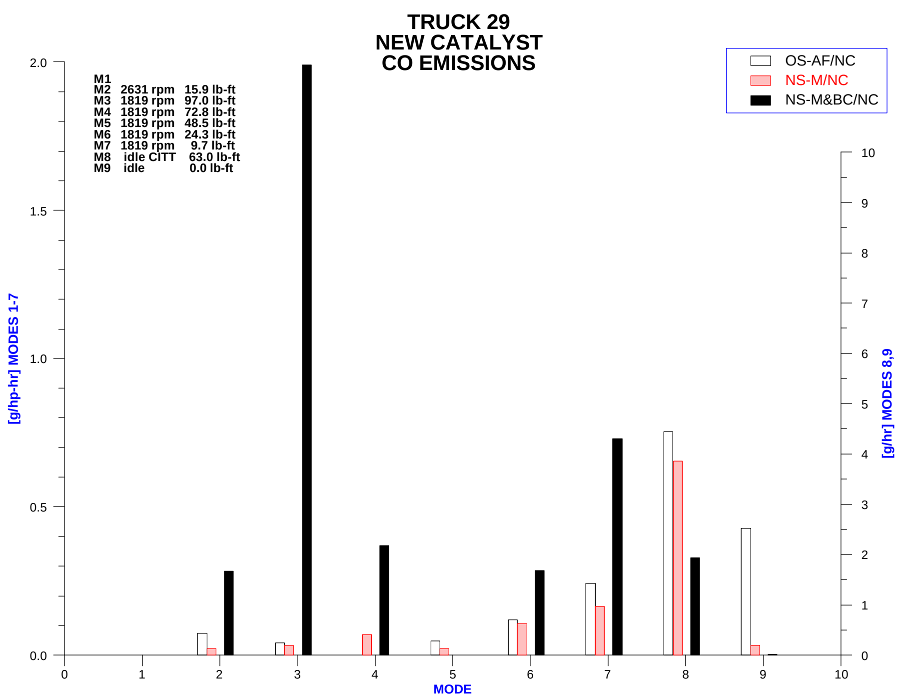

FIGURE 13. TRUCK 29, NEW CATALYST, CO EMISSIONS RESULTS

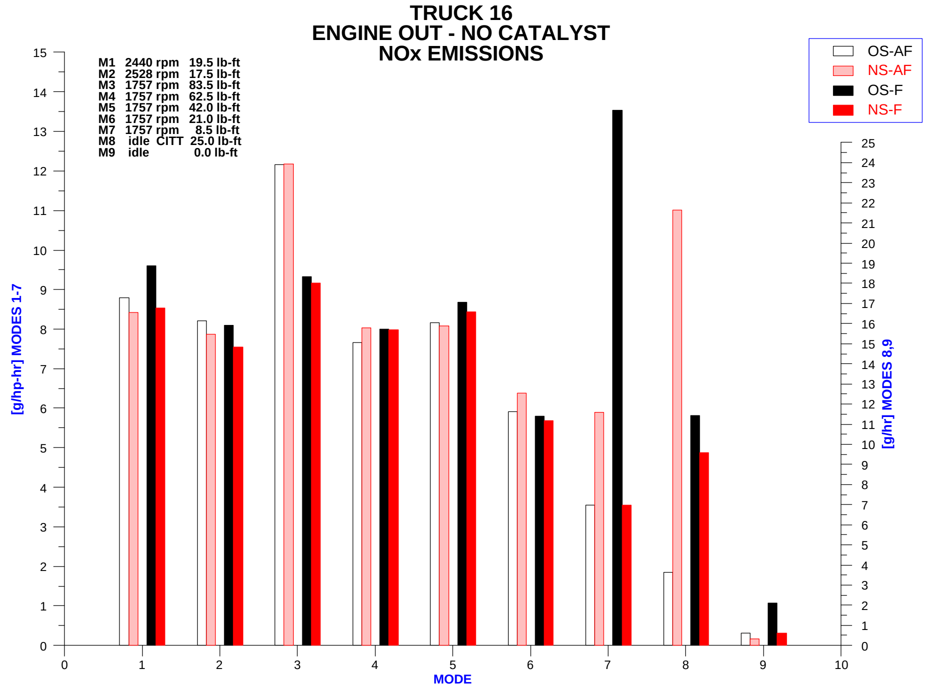

FIGURE 14. TRUCK 16, ENGINE-OUT - NO CATALYST, NO_X EMISSIONS RESULTS

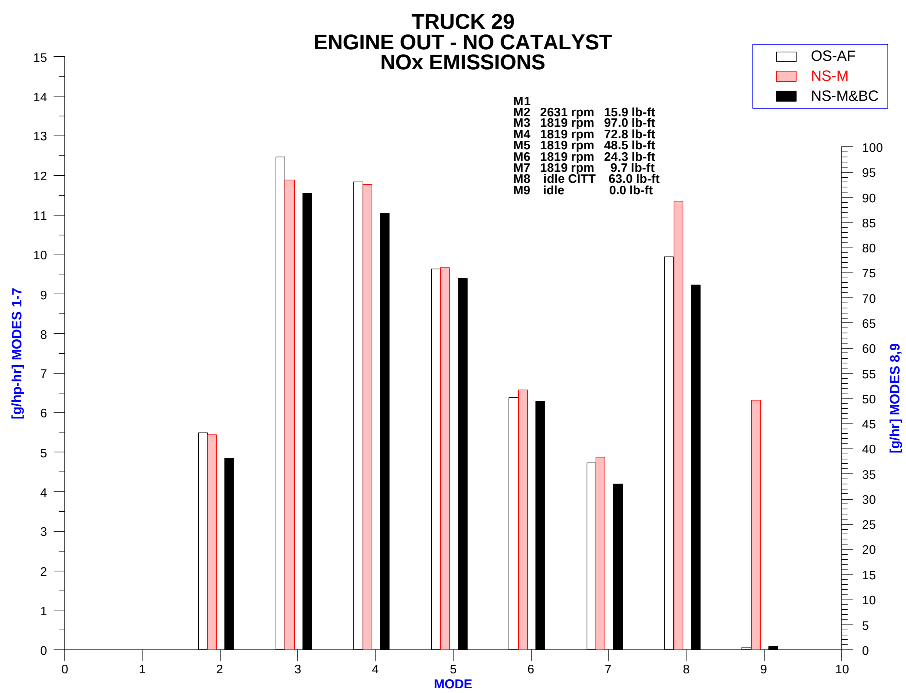

FIGURE 15. TRUCK 29, ENGINE-OUT - NO CATALYST NO_X EMISSIONS RESULTS

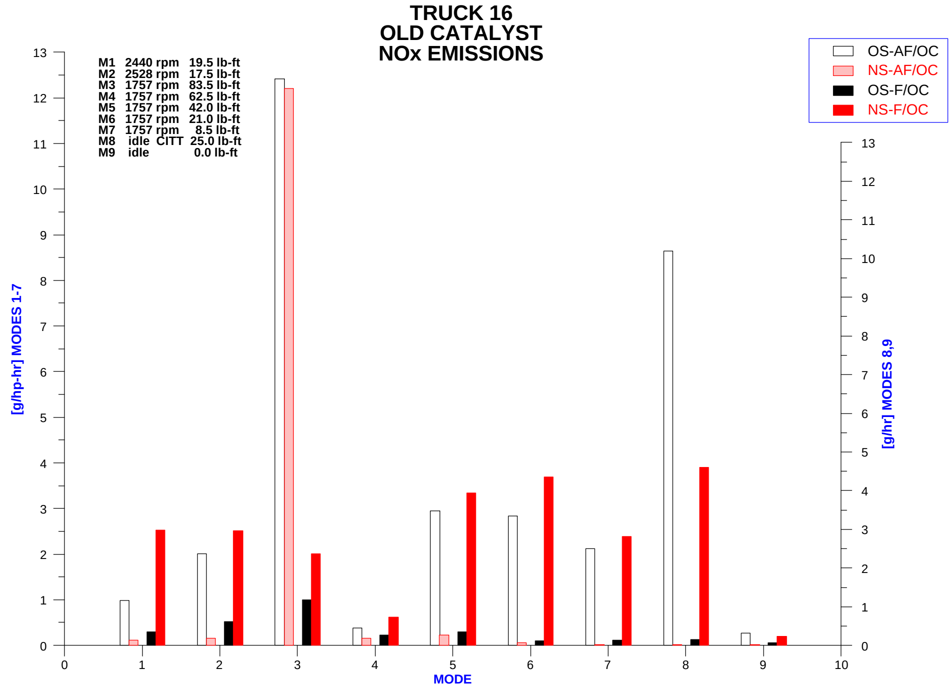

FIGURE 16. TRUCK 16, OLD CATALYST NO_X EMISSIONS RESULTS

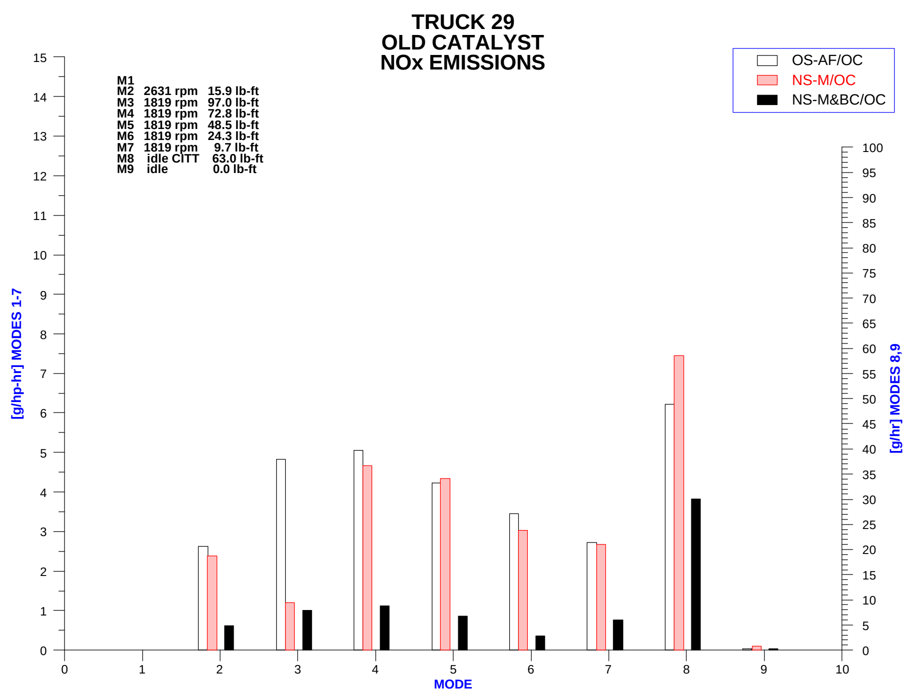

FIGURE 17. TRUCK 29, OLD CATALYST NO_X EMISSIONS RESULTS

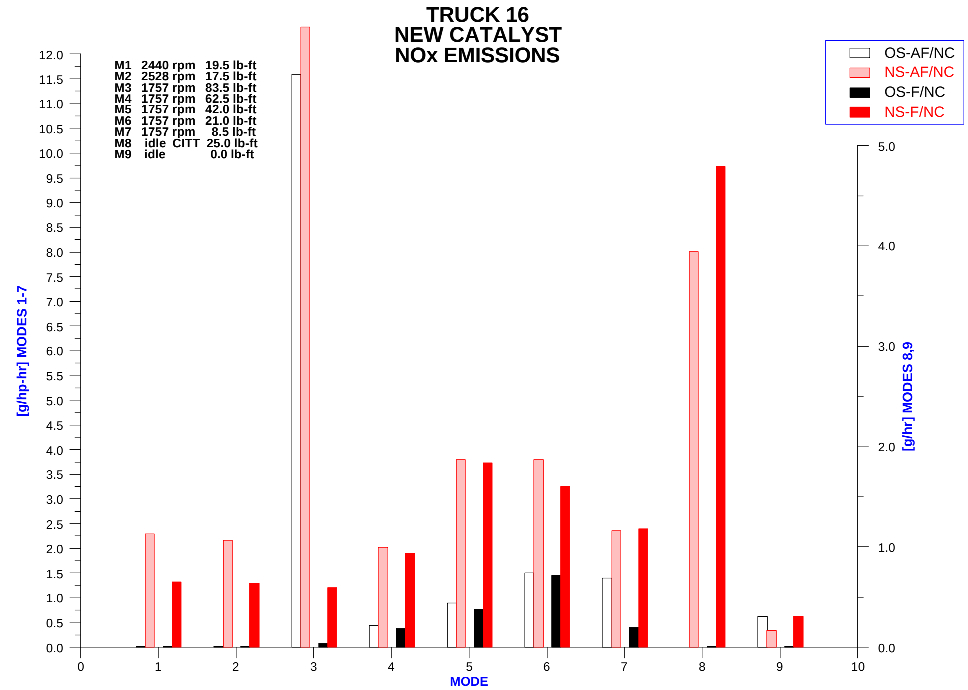

FIGURE 18. TRUCK 16, NEW CATALYST NO_X EMISSIONS RESULTS

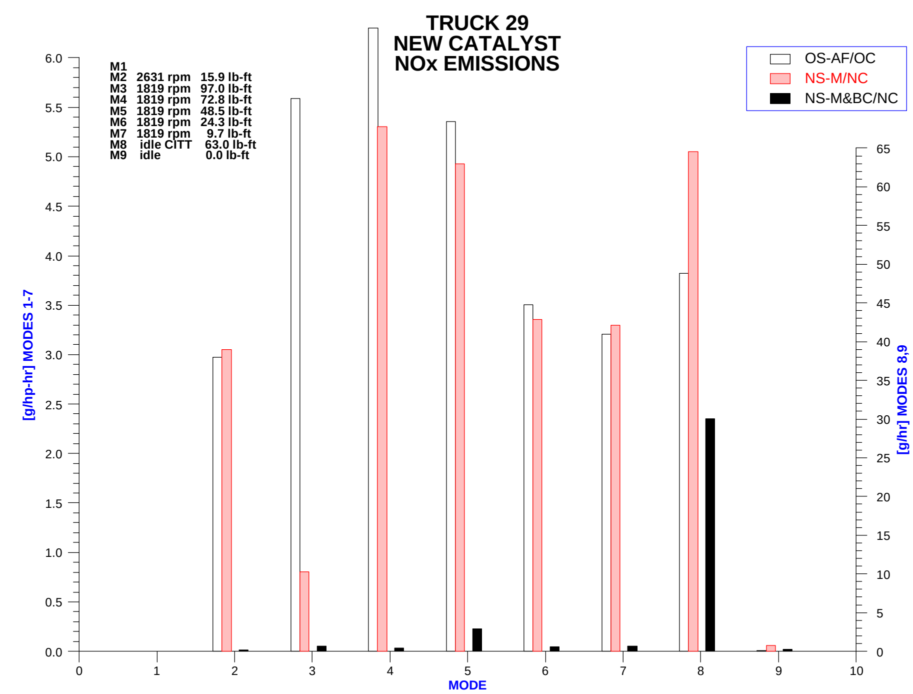

FIGURE 19. TRUCK 29, NEW CATALYST NO_X EMISSIONS RESULTS

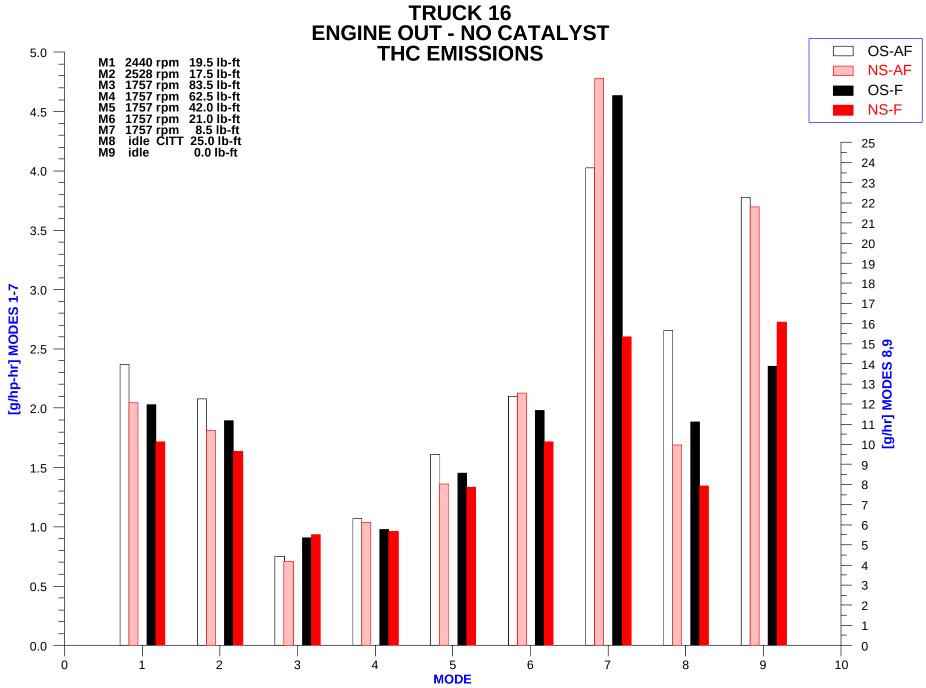

FIGURE 20. TRUCK 16, ENGINE-OUT - NO CATALYST THC EMISSIONS RESULTS

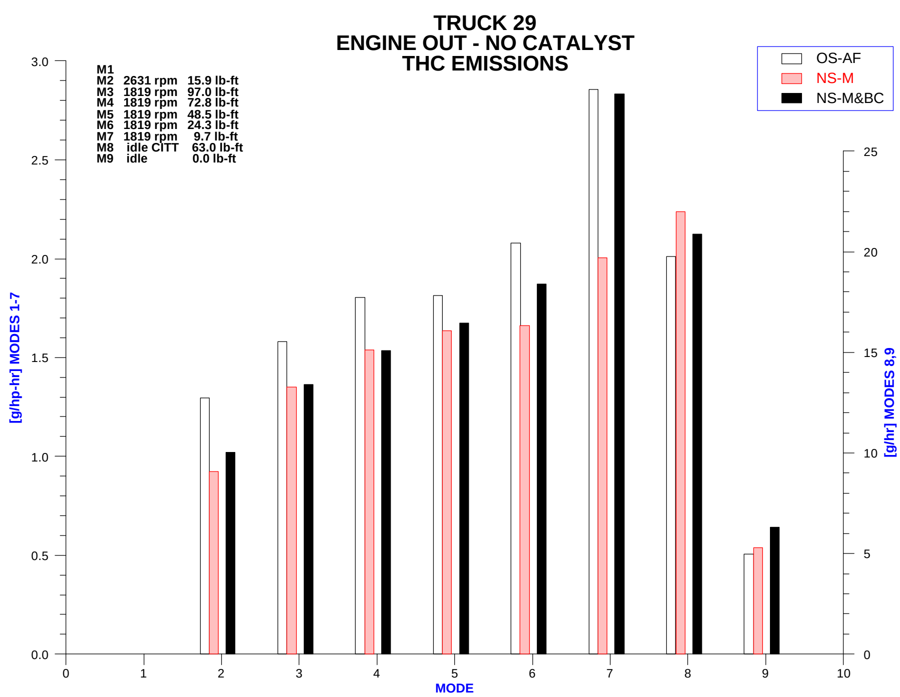

FIGURE 21. TRUCK 29, ENGINE-OUT - NO CATALYST THC EMISSIONS RESULTS

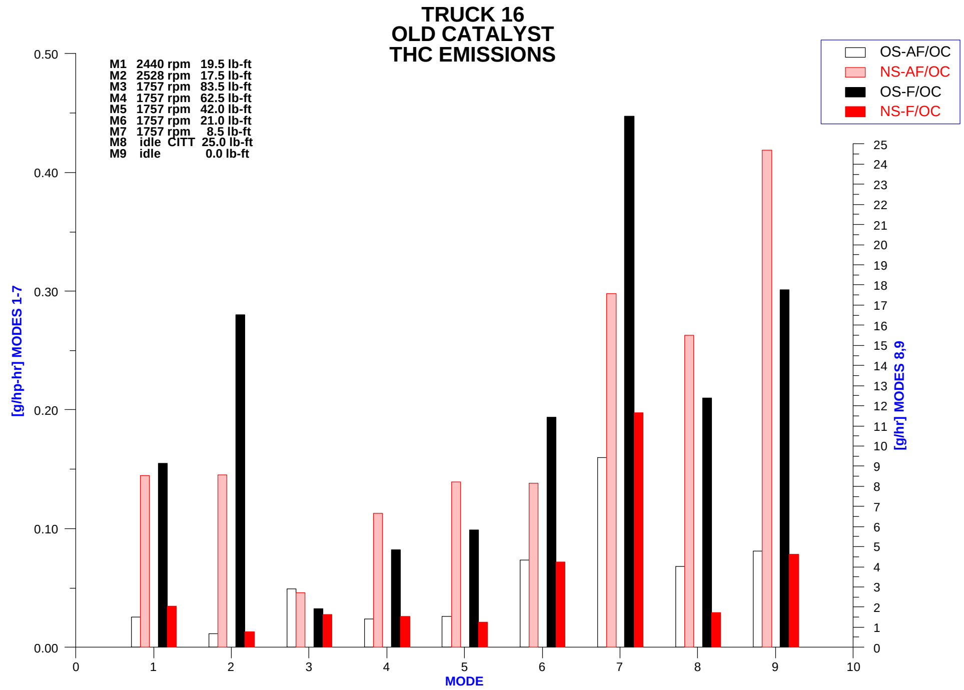

FIGURE 22. TRUCK 16, OLD CATALYST THC EMISSIONS RESULTS

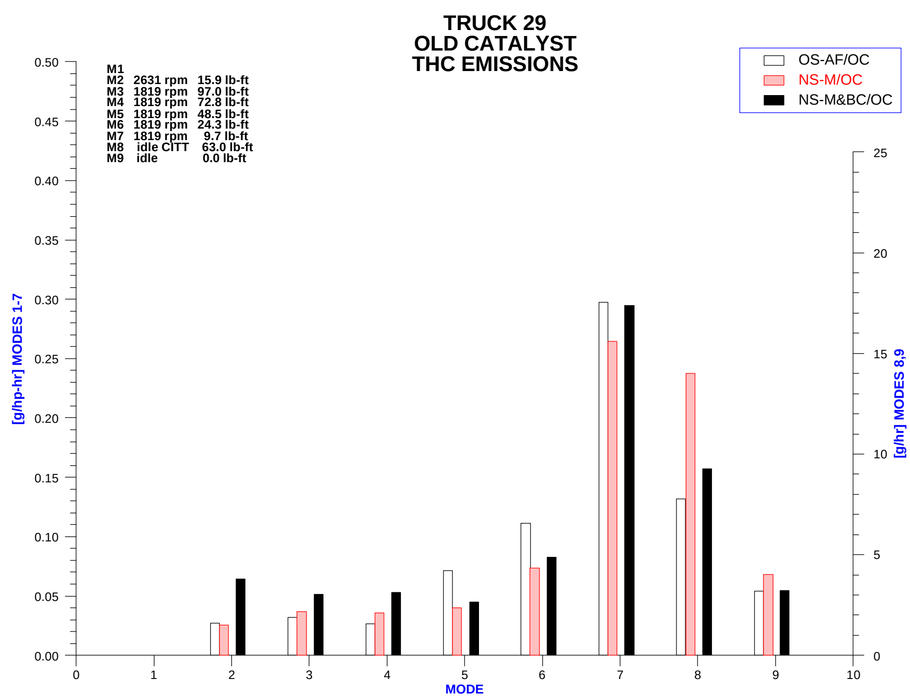

FIGURE 23. TRUCK 29, OLD CATALYST THC EMISSIONS RESULTS

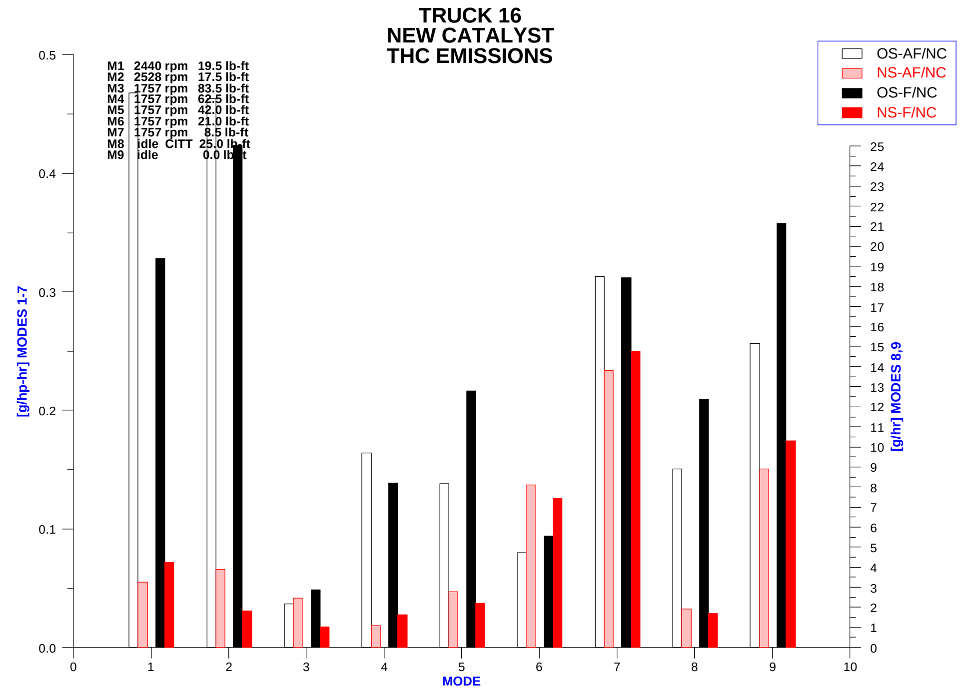

FIGURE 24. TRUCK 16, NEW CATALYST THC EMISSIONS RESULTS

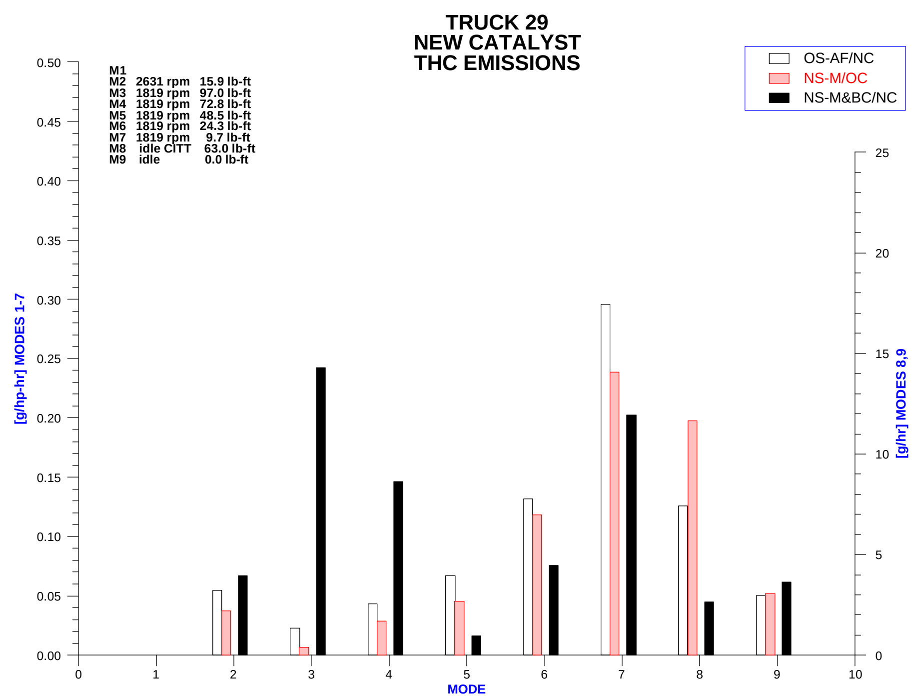

FIGURE 25. TRUCK 29, NEW CATALYST THC EMISSIONS RESULTS

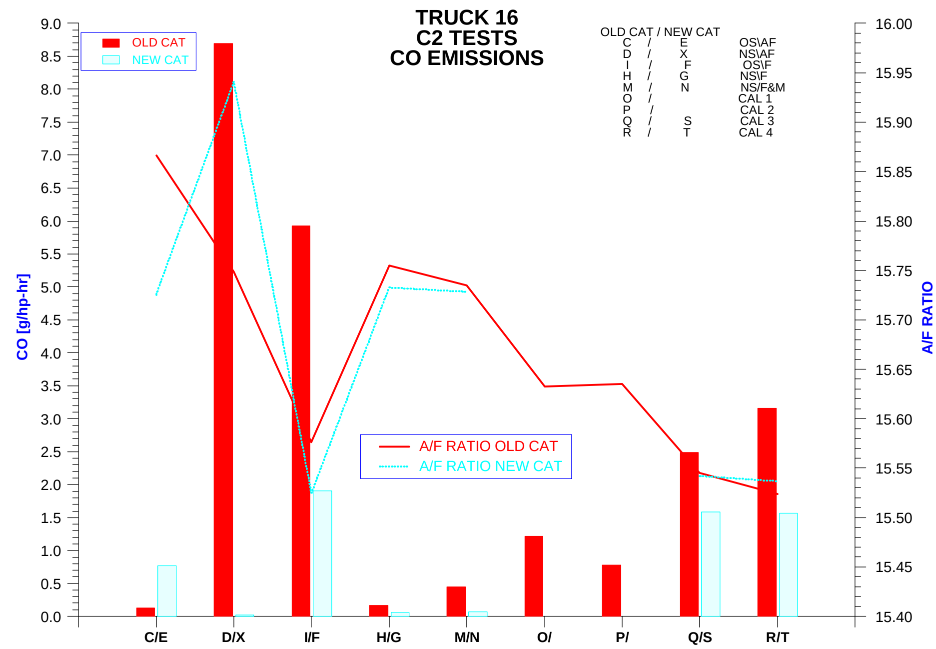

FIGURE 26. TRUCK 16, C2 TESTS, CO EMISSIONS RESULTS

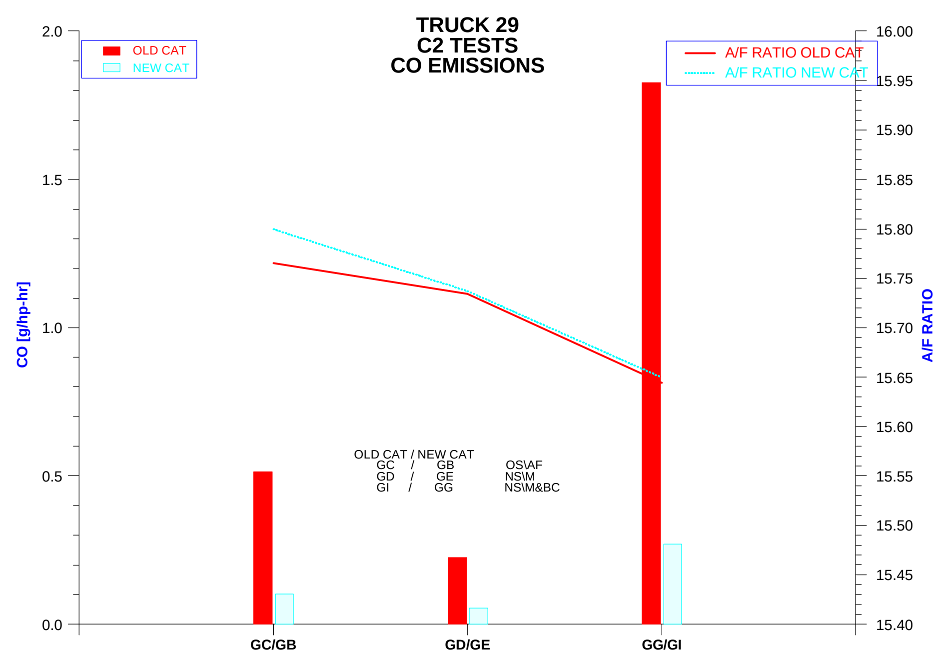

FIGURE 27. TRUCK 29, C2 TESTS, CO EMISSIONS RESULTS

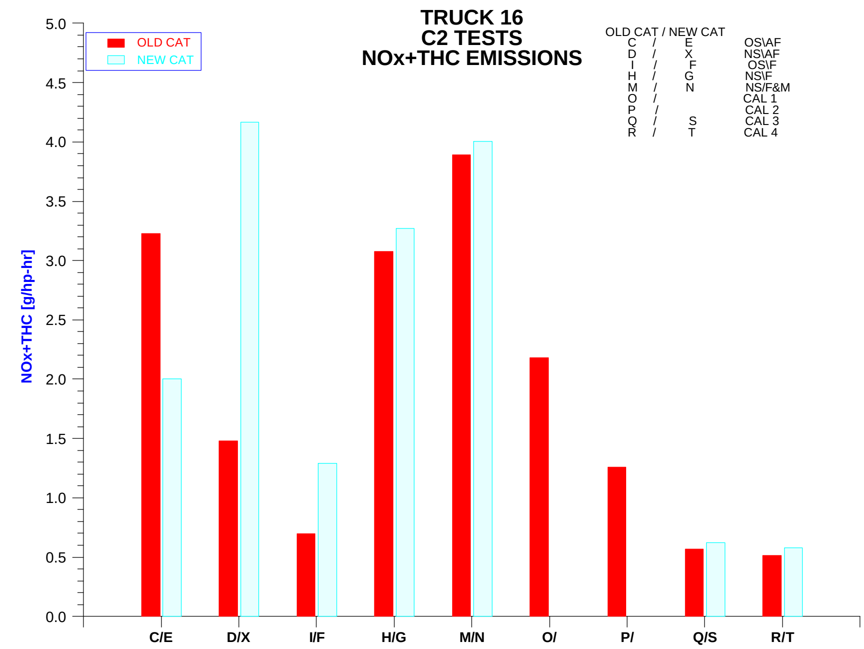

FIGURE 28. TRUCK 16, C2 TESTS, NO_X+THC EMISSIONS RESULTS

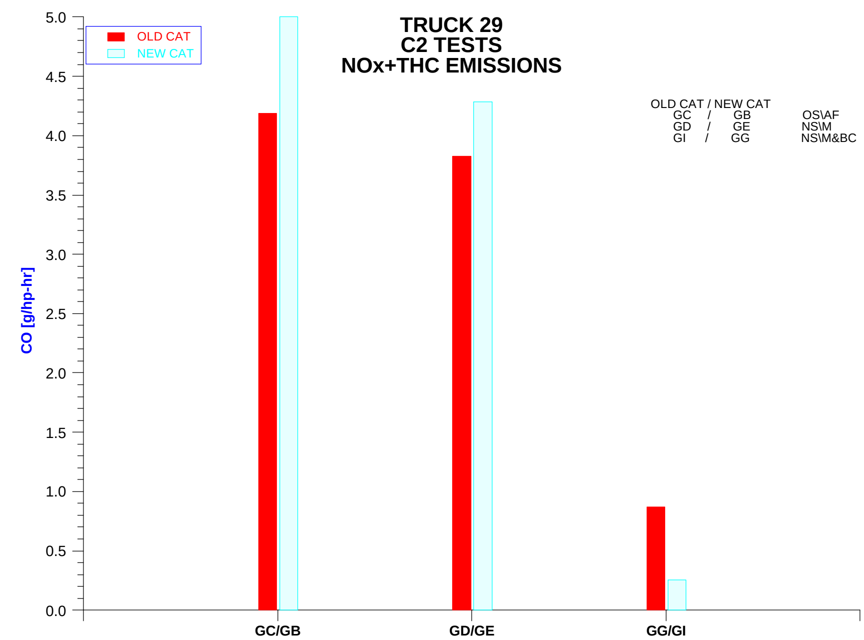

FIGURE 29. TRUCK 29, C2 TESTS, NO_X+THC EMISSIONS RESULTS

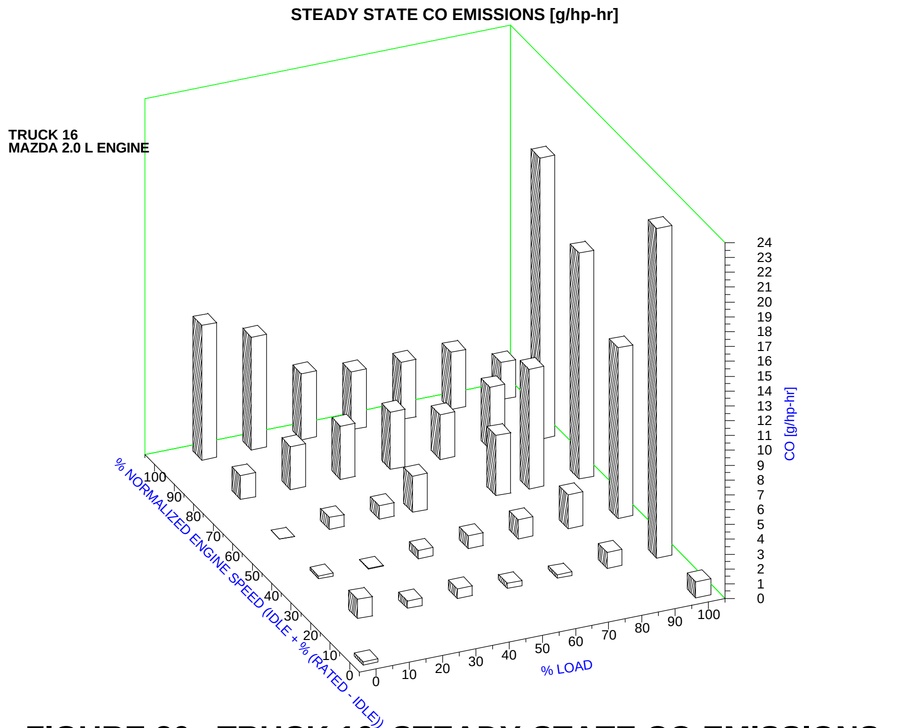

FIGURE 30. TRUCK 16, STEADY-STATE CO EMISSIONS RESULTS OVER NORMALIZED SPEED AND LOAD

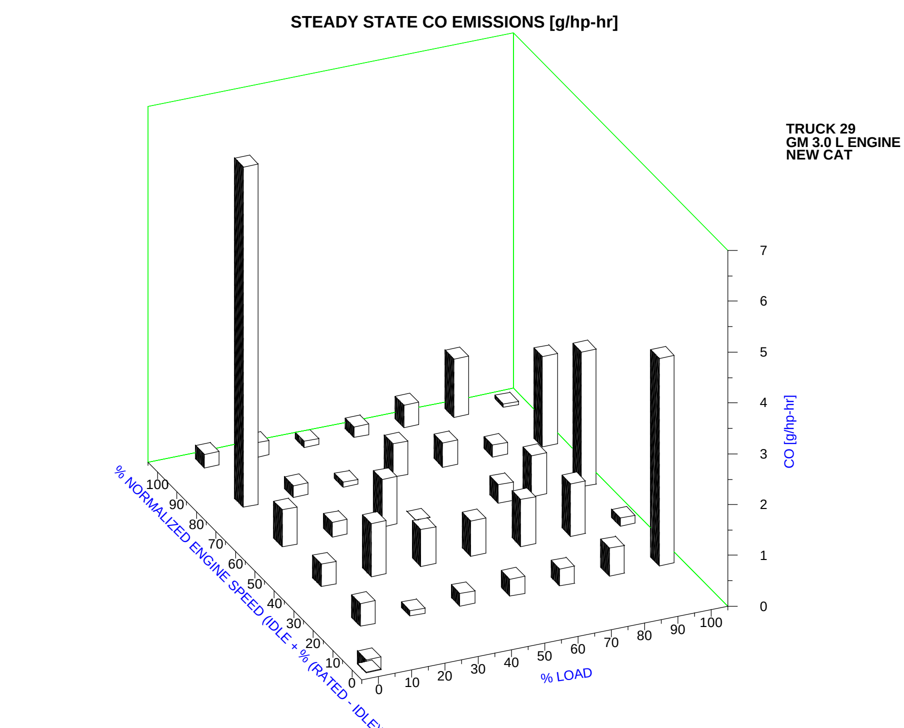

FIGURE 31. TRUCK 29, STEADY-STATE CO EMISSIONS RESULTS OVER NORMALIZED SPEED AND LOAD

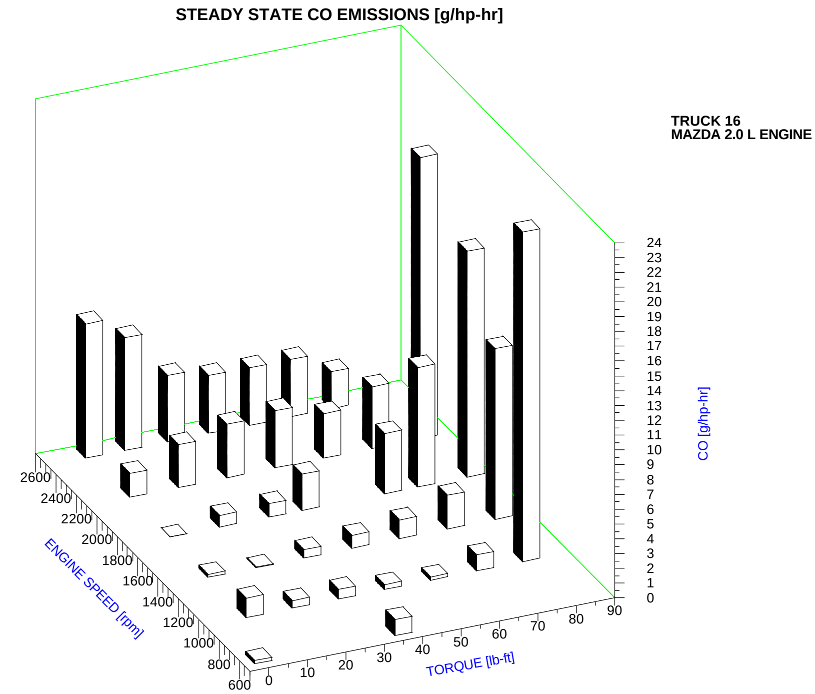

FIGURE 32. TRUCK 16, STEADY-STATE CO EMISSIONS RESULTS

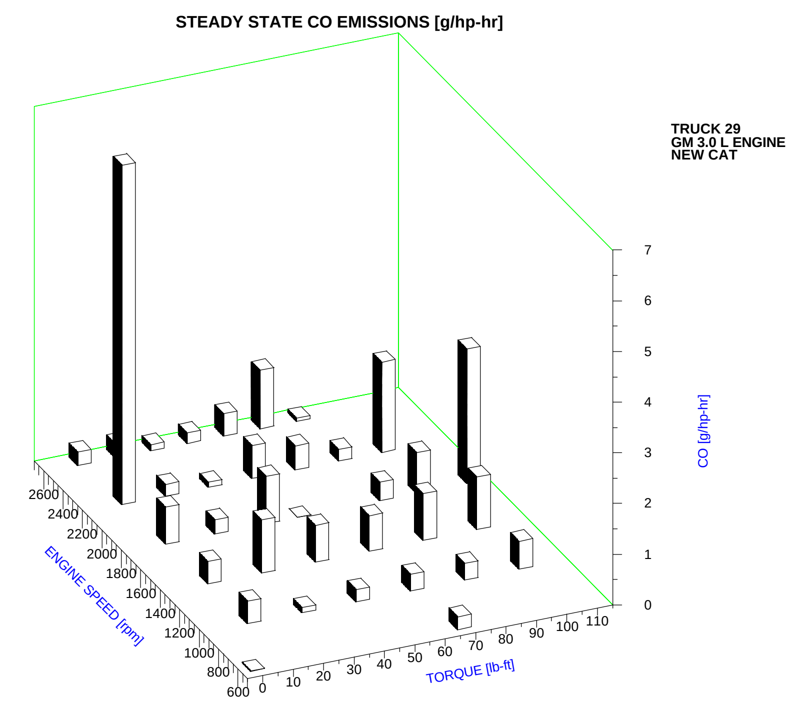

FIGURE 33. TRUCK 29, STEADY-STATE CO EMISSIONS RESULTS

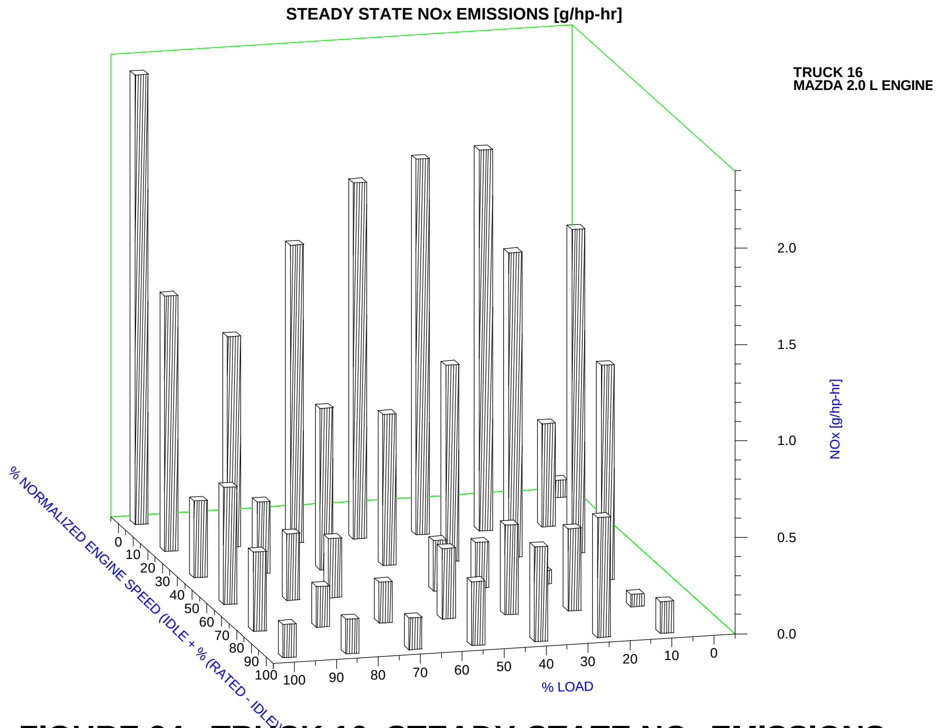

FIGURE 34. TRUCK 16, STEADY-STATE NO_X EMISSIONS RESULTS OVER NORMALIZED SPEED AND LOAD

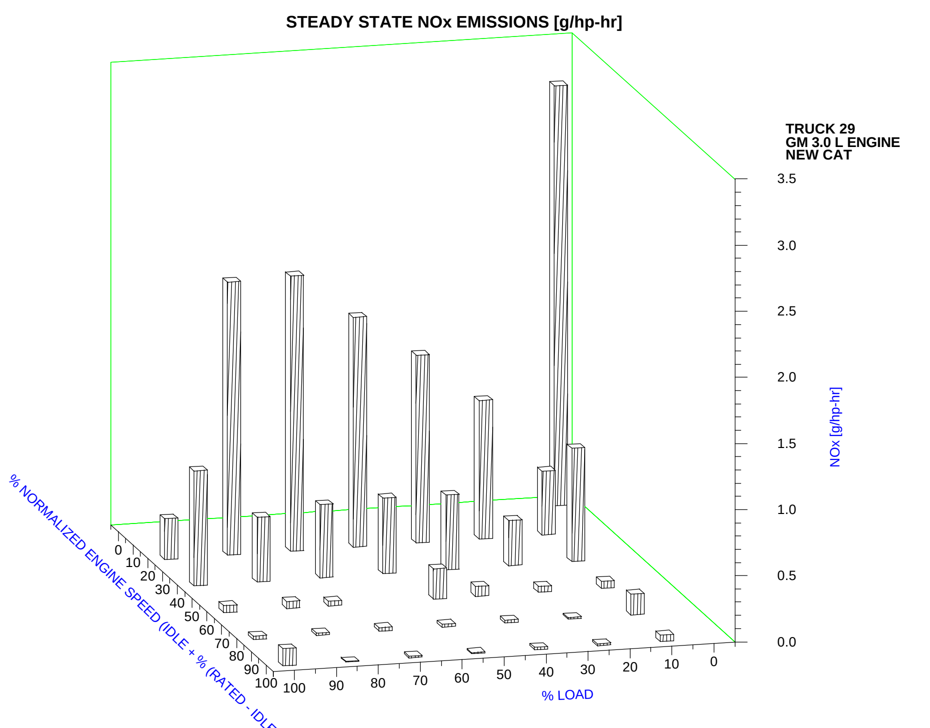

FIGURE 35. TRUCK 29, STEADY-STATE NO_X EMISSIONS RESULTS OVER NORMALIZED SPEED AND LOAD

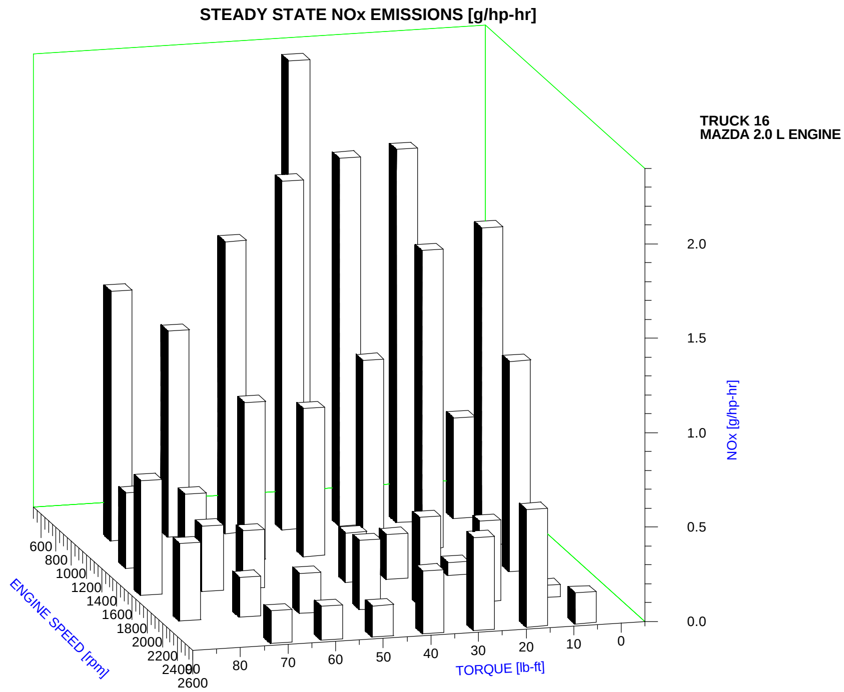

FIGURE 36. TRUCK 16, STEADY-STATE NO$_X$ EMISSIONS RESULTS

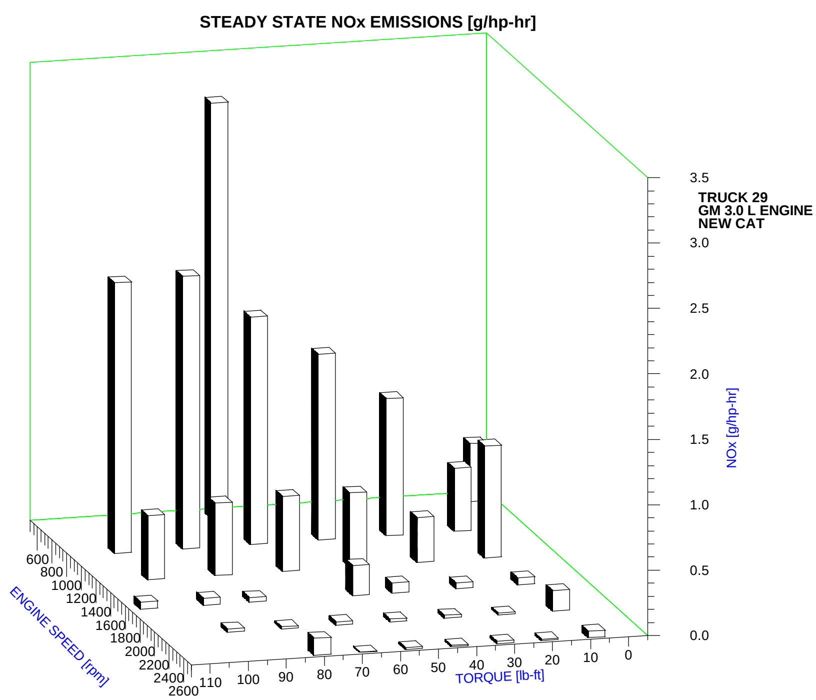

FIGURE 37. TRUCK 29, STEADY-STATE NO$_X$ EMISSIONS RESULTS

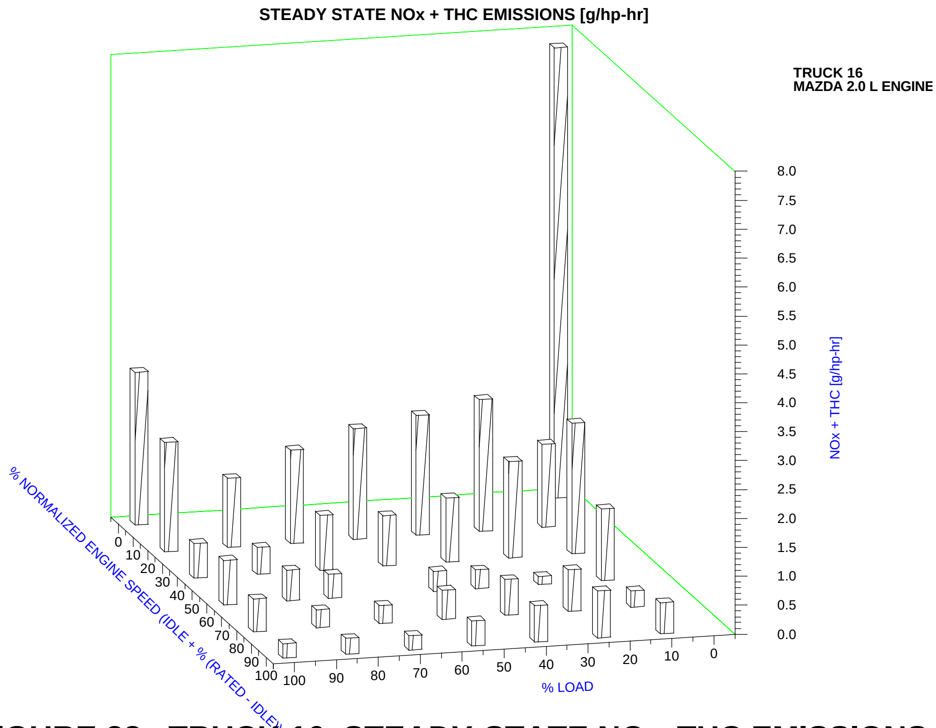

FIGURE 38. TRUCK 16, STEADY-STATE NO_X+THC EMISSIONS RESULTS OVER NORMALIZED SPEED AND LOAD

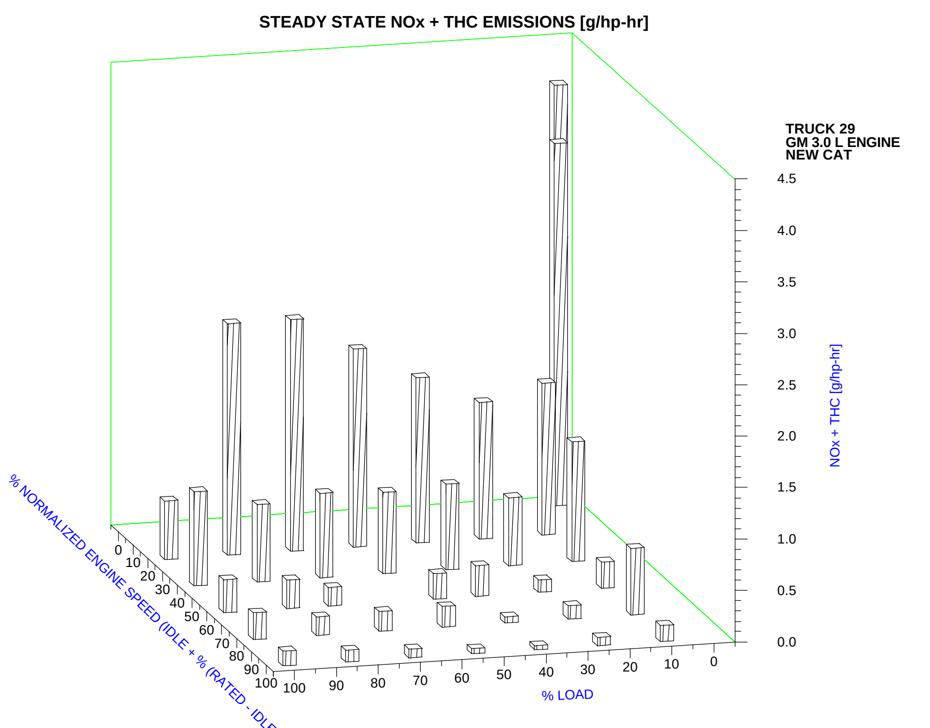

FIGURE 39. TRUCK 29, STEADY-STATE NO_X+THC EMISSIONS RESULTS OVER NORMALIZED SPEED AND LOAD

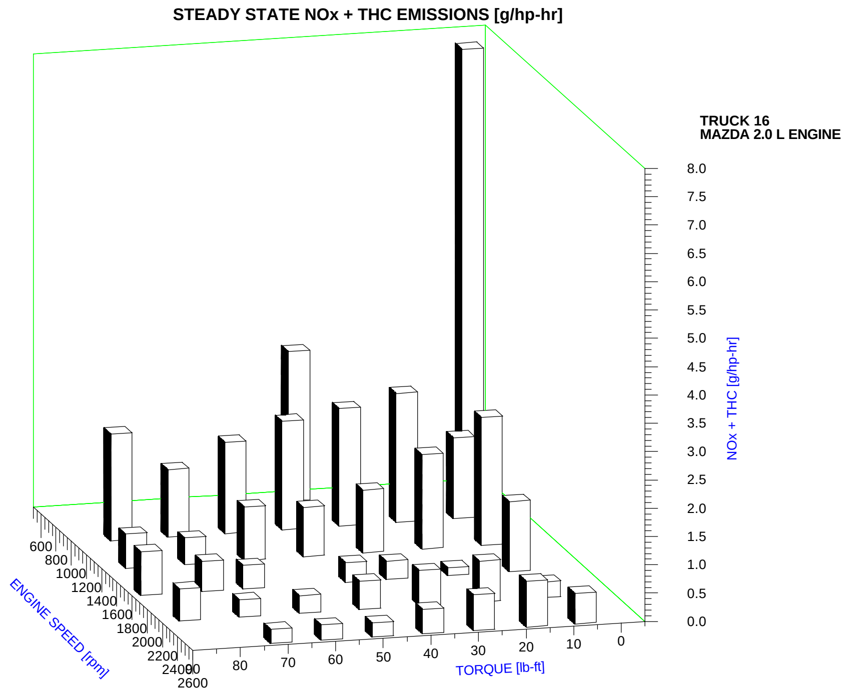

FIGURE 40. TRUCK 16, STEADY-STATE NO_X+THC EMISSIONS RESULTS

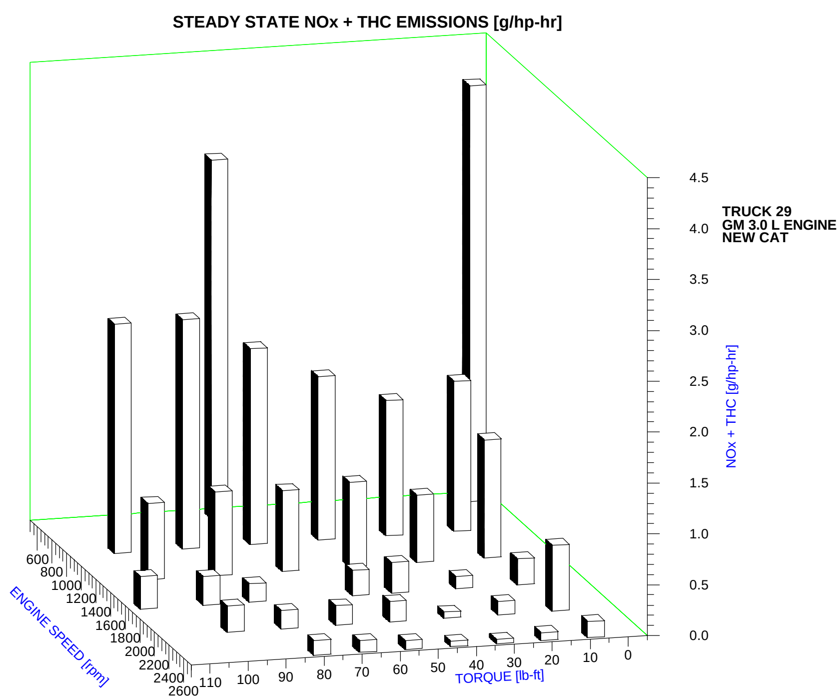

FIGURE 41. TRUCK 29, STEADY-STATE NO_X+THC EMISSIONS RESULTS

2. Transient Test Emissions Measurements

Mazda Engine (Truck 16)

EPA desired to develop transient cycle segments representative of forklift operation from the data acquired in the field. Based on statistical analysis of the data sets, two, five-minute segments were selected as "most typical," and "highest level of transients." Since torque information could not be obtained directly in the field, it was necessary to create a torque signal in the laboratory based on available data. Initially, it was thought that torque information could be developed from a correlation of in-field throttle position, engine speed, and manifold absolute pressure data with a map of steady-state engine operation. After further consideration, a more direct approach was formulated where the engine was commanded in the test cell so as to duplicate the field operating data. This required development of new control algorithms. A very good duplication of the field operation has been achieved for the two, five-minute segments.

Transient cycle emissions have been measured from the Mazda engine using the following cycles:

- Typical forklift
- Highly transient forklift
- Heavy-duty on-highway Otto-cycle federal test procedure (FTP)
- Backhoe loader cycle (BHL)

Results are summarized in Table 6.

TABLE 6. MAZDA ENGINE TRANSIENT TEST RESULTS

Test ID	Cycle	Emissions, g/hp-h					COMMENTS
		THC	CH_4	NMHC	CO	NO_x	
MT-TT1	Typical	0.69			1.09	5.14	As Found, Avg. Of 3 Runs
MT-DD1	H. Transient	0.64			2.57	5.81	As Found, Avg. Of 3 Runs
MT-TT7	Typical	0.60			5.69	1.40	Best Calibration, Old Cat
MT-DD8	H. Transient	0.23			4.25	1.10	Best Calibration, Old Cat
H3	FTP	0.34	0.11	0.24	4.61	0.88	Best Cal, warmed up, Old Cat
H4	FTP	0.76	0.12	0.64	11.96	1.13	Best Cal, With 20 Min Soak, Old Cat
H7	FTP	0.38	0.07	0.31	3.10	2.39	Best Cal, With 20 Min Soak, New Cat
H5	BHL	0.37	0.10	0.27	9.12	0.95	Best Cal, With 20 Min Soak, Old Cat
H6	BHL	0.30	0.07	0.23	4.63	0.79	Best Cal, With 20 Min Soak, New Cat

In the "as found" configuration, the highly transient cycle segment generated higher CO and NO_x emissions. The reverse was observed in the "best calibration" test where higher emissions were created with the "typical" cycle segment.

The backhoe loader cycle (BHL) was developed by SwRI under contract for the EPA from nonroad diesel equipment operating data. For both the BHL cycle and the on-highway transient FTP, the engine was warmed up and then hot-soaked (engine off) for 20 minutes prior to running the cycle. Test H3 was run without a soak. The engine was started from a warmed-up condition, which resulted in significantly lower HC, CO, and NO_x emissions. CFR statistical requirements for test validity were met for the FTP, but could not be met for torque on the BHL cycle due to the governor response during full load portions of the cycle.

III. PLANS FOR THE NEXT REPORTING PERIOD

Task 1 - Normalize engine speed and torque data, and finish statistical analysis for Truck 16. Relay interim data analysis results to SCAQMD, CARB, and EPA.

Task 2 - Install the Truck 29 engine in transient cell and begin testing. Relay interim results to SCAQMD, CARB, and EPA.

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APPENDIX A

SUMMARY
MAZDA 4-121G ENGINE (TRUCK 16)
MODAL EMISSIONS, CATALYST EFFICIENCY, AND
C2 COMPOSITE RESULTS

APPENDIX B

SUMMARY
GM 181 ENGINE (TRUCK 29)
MODAL EMISSIONS, CATALYST EFFICIENCY, AND
C2 COMPOSITE RESULTS

APPENDIX C

MAZDA 4-121G ENGINE (TRUCK 16) EMISSIONS TEST RESULTS

APPENDIX D

GM ENGINE (TRUCK 29)
EMISSIONS TEST RESULTS